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14. ABSTRACT Our goal was to exploit Quantum Confinement Stark Effect (QCSE) to prepare the next generation of nanolasers -- tunable self-modulated nanolasers -- with the ability to provide both high-speed modulation and wavelength tunability. We envisioned to exploit the QCSE in optically pumped nanolasers as a proof of concept. Specifically, we proposed to address the following research objectives, namely: (i) design and investigation of metallo-dielectric nanolasers subjected to an external electric field, (ii) fabrication of optically pumped nanolasers.					
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Report Title

Final Report: Optoelectronics: Low-Energy Tunable Self-Modulated Nanolasers (1.1 SHORT-TERM INNOVATIVE RESEARCH (STIR) PROGRAM)

ABSTRACT

Our goal was to exploit Quantum Confinement Stark Effect (QCSE) to prepare the next generation of nanolasers -- tunable self-modulated nanolasers -- with the ability to provide both high-speed modulation and wavelength tunability. We envisioned to exploit the QCSE in optically pumped nanolasers as a proof of concept. Specifically, we proposed to address the following research objectives, namely: (i) design and investigation of metallo-dielectric nanolasers subjected to an external electric field, (ii) fabrication of optically pumped nanolasers.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

<u>Received</u>	<u>Paper</u>
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TOTAL:

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

<u>Received</u>	<u>Paper</u>
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TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received Paper

TOTAL:

Number of Manuscripts:

Books

Received Book

TOTAL:

TOTAL:

Patents Submitted

Patents Awarded

Awards

Graduate Students

NAME	PERCENT SUPPORTED	Discipline
Pan, Si H	0.13	
FTE Equivalent:	0.13	
Total Number:	1	

Names of Post Doctorates

NAME	PERCENT SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Under Graduate students supported

NAME	PERCENT SUPPORTED
FTE Equivalent:	
Total Number:	

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This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:..... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:..... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):..... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:..... 0.00

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Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

NAME

Total Number:

Names of other research staff

NAME

PERCENT SUPPORTED

FTE Equivalent:

Total Number:

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

In the past, we have experimentally demonstrated different types of novel sub-wavelength resonator designs for room/cryogenic temperature lasing action, such as optically pumped metallo-dielectric laser. We choose to adapt our current laser architecture as a starting point for this project. In this architecture, the gain medium is wrapped with a combination of a dielectric shield and a metal layer. By optimizing the thickness of the low index shield between the metal and semiconductor, the gain threshold of the laser can be substantially reduced such that it is amenable to room temperature operation. In order to exploit the QCSE effect, we have thus adapted the previous architecture by implementing electrical contacts, which enable the generation of an electric field through the nanolaser when a voltage is applied (Fig1). In this new design, a conductive electrode, made by Indium Tin Oxide (ITO), constitutes an additional layer deposited on the dielectric shield layer (SiO₂). The conductive layer is optically transparent both at the pump and laser emission wavelengths, respectively at 1064 nm and around 1550 nm.

This new design will tend to modify the properties of the optical modes supported by the resonator. With this SiO₂ dielectric layer at the bottom, the resonator will be not optimized anymore in terms of quality factor and threshold gain. We then started a new simulation campaign in order to optimize this structure at room temperature. Figure 2 shows the fundamental mode supported by the nanocavity. In figure 3(a), we have represented the evolution of the quality factor and the threshold gain as function of the thickness of SiO₂ bottom-layer while keeping constant all the other parameters. This result shows that the threshold gain does not change for a SiO₂ layer thickness below ~250nm while the quality factor remains at the same value ~1500. By keeping the thickness of the SiO₂ bottom-layer at 100 nm, the ITO layer thickness is varied from 100 to 300 nm (Fig3(b)). We observe that this layer should not exceed 200nm-thick in order to keep a reasonable value of threshold gain of ~100cm⁻¹. These results reinforces our idea that this new architecture would operate as those we have demonstrated in the past.

Besides, we have theoretically investigated the effect of the electric field applied across the gain medium on the tunability and, how this field is going to affect the gain. In the QCSE, an external electric field induces a energy shift of the quantum well levels leading to a shift of the emission wavelength. We have thus estimated this wavelength shift as shown in Fig4. This result shows that it would be possible to tune and switch the emitted wavelength within ~2 nm range. Moreover, when the external electric field, applied along the quantum well growth direction, drifts electrons and holes toward opposite directions, reducing their wave functions overlap and thus resulting in slower absorption rates. This leads to a reduction of the gain as the strength of the electric field is increased. However, the ratio between the gain for zero-electric field and non-zero-electric field, shows a reduction of ~5% for relatively small applied electric field.

In addition, we have also started fabricating the proposed device shown in Fig. 1. The device is fabricated on a wafer consisted of 300nm InGaAsP multiple quantum wells (MQWs) epitaxially grown on top of an InP substrate. The MQW gain region involves nine layers of 10nm In_{0.564}Ga_{0.436}As_{0.933}P_{0.067} well embedded in ten layers of 20nm In_{0.737}Ga_{0.263}As_{0.569}P_{0.431} barrier. Electron beam lithography were performed to pattern the wafer with circles of various radii by using a negative tone resist named hydrogen silsesquioxane (HSQ). The patterned wafer was processed with reactive ion etching (RIE) to create circular pillars of approximately 500nm height (Fig. 5a). Aluminum oxide (100nm) was deposited on top of the etched wafer through atomic layer deposition (ALD) to reduce the field-metal overlap and therefore, the metal cavity loss (Fig. 5b). Subsequently, a 300nm layer of silver along with a 20nm gold capping layer were sputtered onto the sample to confine the electromagnetic field (Fig. 5c). Finally, the devices were attached to a silicon wafer with silver epoxy and the InP substrate was chemically etched away with hydrochloride acid to create an air hole at the bottom of the cavity. We used aluminum oxide instead of the previously proposed silicon dioxide because adhesion between silicon dioxide and silver is poor. The gain medium slips out along with the oxide layer during wet etching of the InP substrate when adhesion between the oxide layer and silver is poor. On the other hand, adhesion between aluminum oxide and silver is good such that the MQW gain is preserved after substrate removal. The next step is to deposit an oxide layer and ITO on top of the gain, which is currently in progress.

Technology Transfer

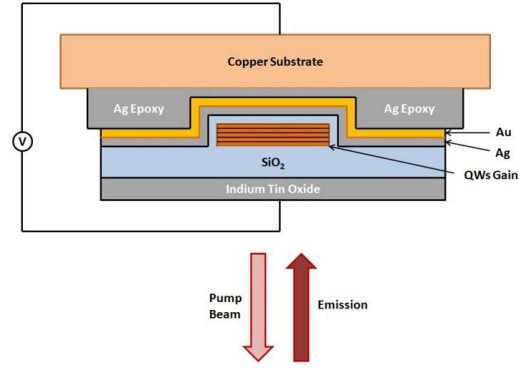


Fig. 1. Schematic of the proposed tunable optically pumped nanolaser.

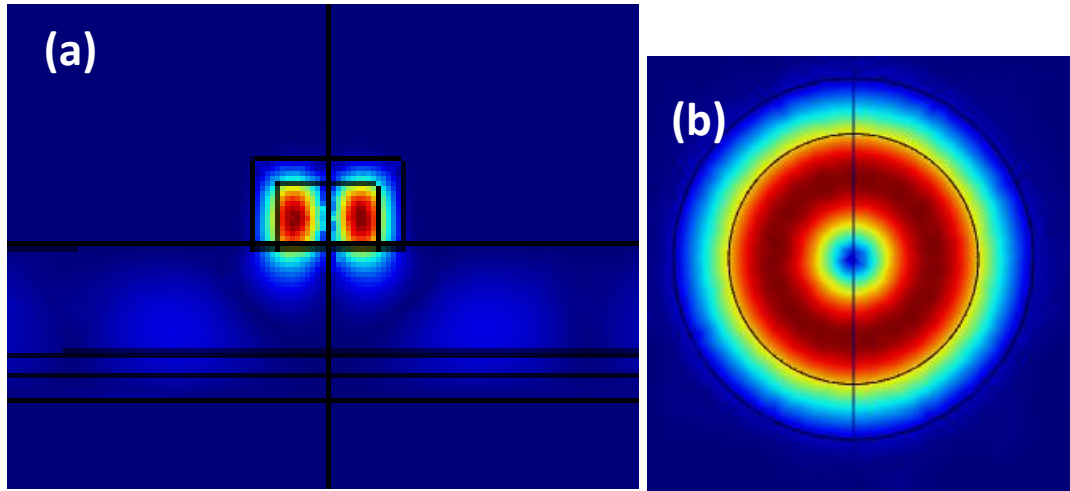


Fig. 2. (a) side (b) top views of the fundamental mode supported by the nanocavity.

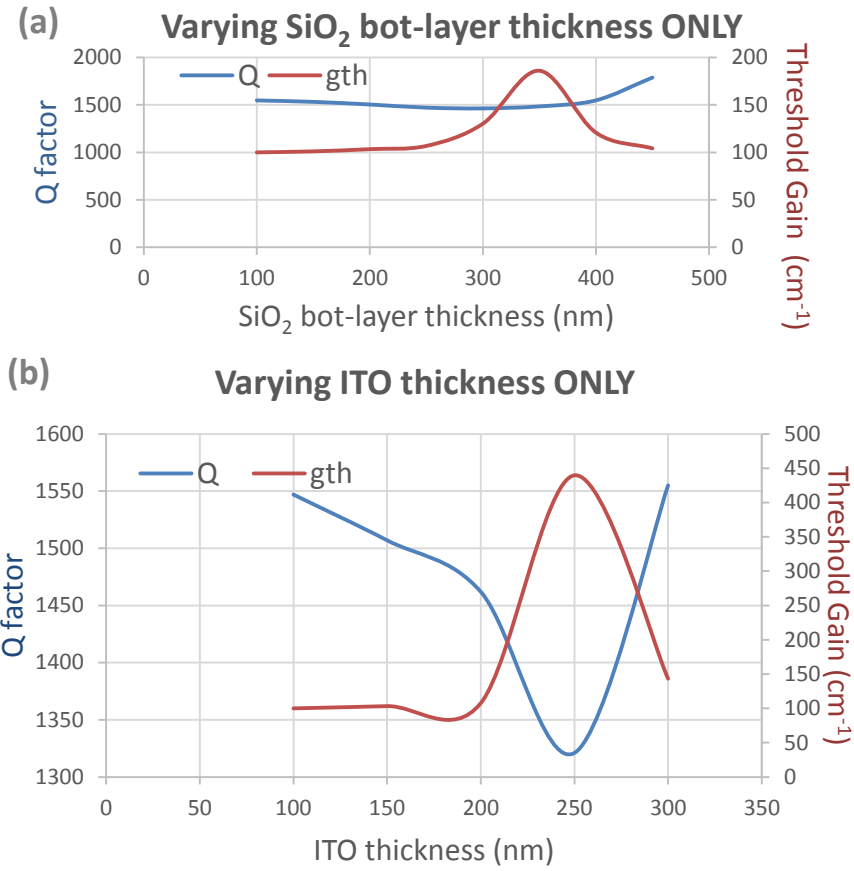


Fig. 3. (a) Evolution of the quality factor and the threshold gain versus SiO₂ bottom-layer thickness. The ITO layer thickness is 100nm. (a) Evolution of the quality factor and the threshold gain versus ITO -layer thickness. The SiO₂ layer thickness is 100nm.

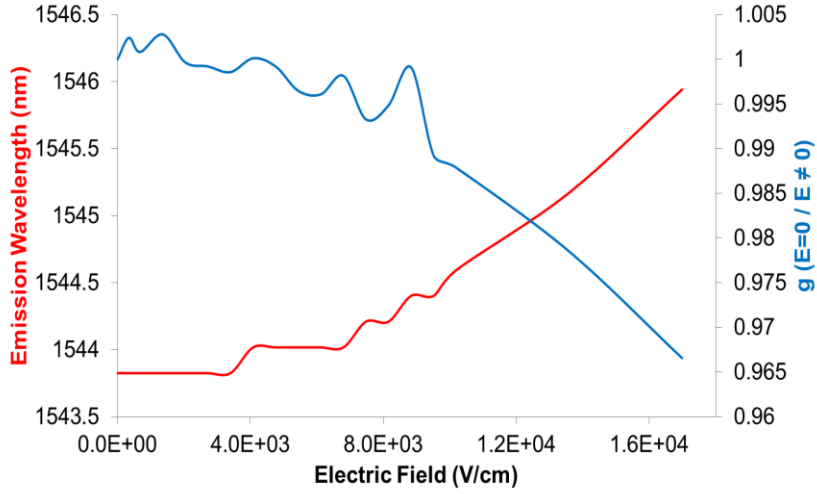


Fig. 4. Evolution of the emission wavelength and the normalized gain with respect of the external electric field.

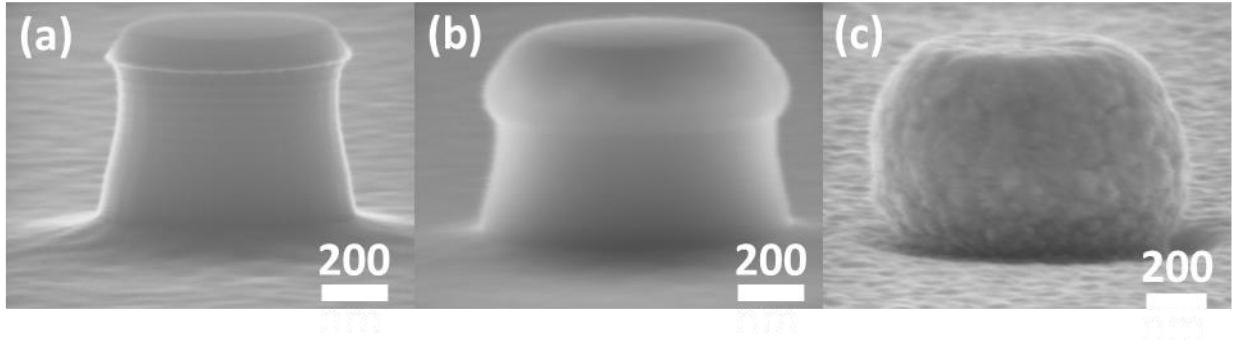


Fig. 5. Scanning electron microscope images of the proposed device after (a) dry etching, (b) aluminum oxide deposition and (c) silver deposition.